Team Reports: University of Washington

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Executive Summary
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Our group has had a diverse year, with members participating in NASA missions, geological and oceanographic expeditions, and diverse laboratory and theoretical studies. Through all, our NAI–sponsored research at the University of Washington has concentrated on the following important astrobiological questions:

1. What are the characteristics of planets that can evolve complex organisms?
2. Where might such planets occur?
3. How does biological complexity evolve on a planet, and how might it end?
4. What are the limits and permissible chemistries of life and how might they arise?

We are beginning the fourth year of research into these questions. Below, our results and progress are summarized based on specific research problems defined in our original proposal.

How often, where, and under which conditions do habitable planets form and persist?

The rapid discovery of ever more extra–solar planets has now made clear that the Universe is filled not only with stars, but also with planets orbiting those stars. Even a decade ago we could not, with confidence, predict how many planets there might be beyond our own solar system. While there was no indication that there was anything special about our own solar system and star that would make us unique in having planets, there was no real data to the contrary. Now there is definite evidence that planet formation is not only common, but might be ubiquitous to every region in our Milky Way Galaxy, and perhaps in most or all of the far flung galaxies making up the known Universe. We have gone from asking, “how many stars have planets,” to “how many planets have life?”

We define a habitable planet as a solid body capable of supporting life as we know it. The study of extra–solar habitable planets involves a broad interdisciplinary approach that extends from understanding how planets are formed, to understanding the conditions that allow such life to originate, survive, and evolve.

During the past year (2003−2004), Lucio Mayer and Tom Quinn have continued performing simulations of giant planet formation by fragmentation of a gaseous disk, and this work is progressing on several fronts, with special attention to the formation of binary star systems. Lufkin and Quinn have published their work on giant planet migration, showing that migration is not smooth, but probably chaotic. This work continues with a more complete look at migration dynamics. Barnes and Quinn, in collaboration with Lissauer (Ames), continue their simulations of planetesimal accretion in the terrestrial region, and now are concentrating on the timescales for runaway growth.

Finally, Barnes, Quinn, and Raymond continued to investigate the stability of newly discovered extraplanetary systems.

What caused the delivery and retention of organics and volatiles through Earth history?

The volatile and organic composition of impacting bodies is a key factor in the evolution of habitable planets. What are the relative roles of large comet and asteroid fragments and interplanetary dust particles (IDPs) in bringing these materials to a planet? Principle Investigator (PI) Brownlee has made major discoveries about the nature of cometary composition and construction through the successful flyby of the Stardust mission. Also, Kress and Brownlee, in collaboration with George Cody, have investigated the thermal alteration of organic material entering the atmosphere in small extraterrestrial particles. Matrajt and Brownlee worked on a variety of problems related to the nature and abundance of organic materials in small extraterrestrial materials that enter the Earth's atmosphere. They have developed methods for mounting and handing micrometeorites for organic studies by electron energy loss spectroscopy (EELS) in the transmission electron microscope. This work has been very successful but a challenge due to multiple sources of contamination and substrate interference. This work is yielding direct information on the fine−scale distribution and composition of organic materials in small cometary and asteroidal particles. Working with S. Pizzarello and S. Taylor , they determined the a −aminoisobutyric acid (AIB) amino acid content of micrometeorites recovered from pre−industrial ice at the South Pole.

How do mass extinctions and impacts affect the evolution and survival of complex organisms, i.e., the long−term habitability of planets?

Mass extinctions are short−term events that kill off a significant proportion of a planet's biota, and on Earth have been of greatest consequence to more complex organisms such as metazoans. Surface life is vulnerable to major planetary catastrophes, for example, impact of a large comet or asteroid, radiation and particles from a nearby supernova, or catastrophic climate changes such as intense intervals of greenhouse heating or Snowball−Earth type episodes. It is now known that at least one of the major mass extinctions was caused by large body impact, and we would very much like to know if others as well are related to this. The major line of study involves the study of impact craters and their history.

Impact cratering involves evaluation of projectiles, which, to first order, is a measure of the asteroids and comets passing in near–Earth space. More broadly, it involves the origin of those objects, the orbital evolution of the time of their existence, and at least in the case of asteroids, a series of collision and fragmentation processes that occurred in the asteroid belt. Once the material is in near–Earth space, it involves the evaluation of the material passing through atmospheres of various densities (and in some cases not passing through the atmosphere), and then the mechanism of the hypervelocity impact event itself. The physics of the impact include the explosive release of the kinetic energy, which produces the vaporization and melting of rocks, and excavation of material, not only as an eject blanket in the immediate vicinity of the crater, but in the case of large impact events (which can be biologically significant), the ejection of debris through the atmosphere into space, where it can then envelope the entire planet. The biological consequence for the sudden release of this energy can occur on many scales, from affecting individuals, to the death of species and even removal of entire ecosystems or biota. The mechanics, biological, and geological consequences of impact cratered is an enormous field in the very sweep of its questions.

During the past year, two major mass extinction boundaries were studied: the Permian–Triassic (P/T) boundary in Africa and Canada , and the Triassic–Jurassic (T/J) boundary in the Queen Charlotte Islands , Nevada , Italy , and the Newark Basin . Isotopic and paleontological results from these sites are now either in progress or are finished. Our new work suggests that neither the P/T nor T/J mass extinctions were caused by large body impact.

What can we learn from the geological and fossil record about the evolution of eukaryotes and metazoans?

Research by co–I Buick and his group continued in the following six areas: late Archean – early Paleoproterozoic hydrocarbon biomarker molecules, early Archean sulfur isotopes, metamorphism of early Archean biosignatures, nutrient availability (N, P) in Archean oceans, geochronology of a late Archean flood basalt province, and diamond drilling of astrobiologically significant Archean and early Proterozoic sedimentary horizons in the Pilbara Craton of Australia. Field work was conducted on early Archean supracrustal rocks of the Warrawoona and Coonterunah Groups in the Pilbara Craton, Australia . Principal outcomes showed that cyanobacterial and eukaryotic geolipids are present in rocks half a billion years before other fossils of these groups appear in the geologic record and that molecular fossils can survive for much longer under high–temperature regimes than previously expected. Also, a thorough review of the Archean sulfur cycle and constraints upon sulfur isotopic fractionation confirmed the existence of microbial dissimilatory sulfate reduction in ~3.5–billion–year–old oceans, establishing that complex metabolic pathways and peripherally branching bacterial phyla had already evolved.

Further research was performed in 2003–2004 on Archean hydrocarbon biomarker geochemistry, sulfur isotopic fractionation, and Paleoproterozoic hydrocarbon preservation in fluid inclusions. Planning is well underway for planned deep diamond drill coring of three well–preserved sedimentary intervals (Hamersley–Fortescue, Warrawoona–Coonterunah, and Tumbiana) in the Archean Pilbara Craton, to test syngenicity of hydrocarbon biomarkers and provide unweathered geochemical samples for redox−sensitive environmental indicators.

Co−I Warren has been investigating the ancient Snowball−Earth episodes. During a Neoproterozoic Snowball−Earth event, the ocean surface conditions would determine both the surface climate and the locations for survival of surface life. A process that may be important in the tropical zones (where evaporation exceeds precipitation), as sea ice sublimates, is accumulation of a crust of sea−salt on the ice surface. This can only happen on ice below the eutectic temperature of NaCl brine, −22.9 deg C, but such temperatures are expected on Snowball Earth, even at the equator. No modern surrogate is known to exist in nature now, but we can investigate these processes in our cold−room laboratories. The salt that would accumulate is not NaCl but rather $NaCl{\cdot}2H_2O$, "hydrohalite," which has not received much investigation. Dr. Bonnie Light is collaborating with Warren on this project. She has begun preparations for laboratory studies on (a) migration rates of brine inclusions and salt crystals in ice at low temperatures, (b) the accumulation of salt on sublimating artificial sea ice, (c) suppression of sublimation by a salt crust, (d) cohesive properties of hydrohalite crystals (to determine whether wind will dislodge them), and (e) the absorption spectrum of hydrohalite.

What can we learn from the physiology and molecular characteristics of extant life about the evolutionary pathways by which microbes and their communities evolve, and by which complex organisms originate?

During the past year co−I Staley and his group focused on determining whether the bacterium, *Prosthecobacter dejongeii* , which has alpha− and beta−tubulin analogues previously found only in eukaryotic organisms, contain other eukaryotic proteins. To carry out this work, they compared the genome of *P. dejongeii* with 347 Eukaryotic signature proteins (ESP) from a published list. In addition to *P. dejongeii,* two additional bacteria were included as control organisms, *Gemmata* Wa−1 of the Planctomycetes phylum, and *Caulobacter crescentus* of the Proteobacteria. The protist, *Trypansoma brucei* , was used as a eukaryotic control. *Prosthecobacter dejongeii* had unique ERGO blast matches to alpha−, beta−, and gamma−tubulin, Set2, a transcriptional factor associated with eukaryotic DNA, and LAMMER protein kinase for a total of 12 high ESP matches altogether. *Gemmata* Wa−1 shared six of its 19 high ESP matches with *P. dejongeii* , and that information, coupled with other genomic data, provides strong support that these two phyla are related to one another. If the ESP list is an accurate listing of unique eukaryotic proteins, the low number of high matches between the proteins of these two bacteria with the list raise strong doubts about these organisms being direct ancestors of the Eucarya.

Co−I Leigh used a different approach by continuing his examination of lineages of methanogens. The genome sequence of *Methanococcus maripaludis* is key to studying the evolution of the methanococcal lineage. The genome sequence has been completed and made publically available. A paper on the functional annotation has been submited. Another goal of the project is to use the genetic tools available for *M. maripaludis*, in concert with the genome sequence, to identify the minimal set of genes that is essential for viability. For this purpose and others, Leigh and his group have devised an efficient method for producing gene deletions in *M. maripaludis* **.** They have also carried out an analysis of lateral transfer of genes involved in utilization of alanine as a nitrogen source.

The nature of early Earth communities

A second way to examine the ancient Earth is through study of microbial communities that likely resemble those of the Precambrian. These communities include those found in (a) anaerobic and photosynthetic microbial mats and biofilms, (b) the sub−seafloor associated with deep−sea hydrothermal vents, and (c) water ice. Co−I Stahl continued to characterize microbial populations in two extreme systems: microbial mats inhabiting hypersaline evaporation ponds (Guerrero Negro, Baja California , Mexico) and associated with hot springs (Yellowstone National Park). Mat population structure was characterized at two spatial scales using polymerase chain reaction (PCR)−amplified rRNA genes: horizontally, over distances up to a kilometer, and vertically at submillimetric scales. Although distribution of dominant populations was stable across large distances (~500m), some variation was observed at fine vertical scales (mm). Diel migration was revealed by significant variation between night/day population profiles, suggesting that some sulfide−oxidizing bacteria may enter the overlying water column at night when oxygen becomes limiting. Parallel analyses of greenhouse mats (with and without sulfate) maintained by members of the Early Microbial Ecosystem Research Group (EMERG) group at NASA Ames revealed few changes in population structure associated with sulfate limitation. However, significant differences were detected between rooftop and field mats. In particular, dominant phototrophs shifted from cyanobacteria to sulfur bacteria, regardless of sulfate treatment.

In Yellowstone, work focused on the enrichment and isolation of thermophilic sulfate reducing prokaryotes (SRP) from three hot springs using a variety of electron donors (organic or hydrogen) at 60°C or 80°C, identifying novel populations by sequencing of 16S rRNA and DSR genes. Sulfide production was observed at 60°C on all substrates. In contrast, sulfide was produced only at 80°C on hydrogen, either autotrophically or with acetate as an alternative carbon source. Sulfide was also produced in enrichments on hydrogen using sulfur, sulfite, or thiosulfate as the electron acceptors, at both 60°C and 80°C. In agreement with the observed lower metabolic diversity at higher temperatures, microscopic analysis of these enrichments revealed a lower number of morphotypes at 80°C than at 60°C. The observation that only hydrogen, among the various electron donors tested, supported the growth of SRP at 80°C argues for the importance of lithotrophic metabolism in these hydrothermal systems.

Metabolism in extreme environments.

Another approach to understanding the habitability of planets is to consider the range of extreme environmental conditions on Earth that support life. For example, the detection of water ice and/or submarine hydrothermal vent systems on another planetary body would satisfy some of the key criteria for habitability, and this area has been investigated by co−I Deming and her group. Laboratory observations of bacterial motility and field observations of bacterial attachment led to the testable hypothesis that a temperature threshold exists in ice formations (–10°C in sea ice), below which bacteria cease moving as a means to locate optimal resources and conditions and instead become attached to a surface (first–stage biofilm formation), which allows for continued activity down to –20°C (lowest temperature tested yet). The University of Washington (UW) team continued to pursue questions on microbial activity and evolution in subzero salty habitats, taking a multi–faceted approach that includes studies of Bacteria, Archaea, viruses, exopolymers and extracellular enzymes. Much of this work was done while locked in polar ice on an icebreaker. The phenomenon of attachment or sorption to surfaces (first–stage biofilm formation) under extreme conditions of temperature and salt concentration provides an important focal point. Although much of our work is influenced by NAI objectives, specific accomplishments this year stem from three efforts. Postdoctoral work by Karen Junge has yielded evidence that high molecular weight polymeric substances (EPS), derived from the spent medium of cold–adapted bacterium *Colwellia psychrerythraea* strain 34H, facilitate bacterial activity (incorporation of tritiated leucine into macromolecules) at temperatures below –20°C (Junge et al., in preparation). This work reinforces the importance of EPS to microbial survival (and continuing evolution) in deeply frozen environments, as well as the potential of EPS as biosignatures on icy planets and moons.

The variety of life

The University of Washington team has added Stephen Benner to its group. Benner and his colleagues have been investigating alternatives to “life as we know it,” as well as studying chemical pathways to the formation of RNA and other biological molecules and materials. Benner has looked in particular at the “RNA–first” hypothesis by looking at avenues of prebiotic chemistry that includes borate minerals. Work still continues on the outstanding problem of RNA instability.

The role of plate tectonics

Co–I Solomatov has been studying the role of plate tectonics in Astrobiology. Plate tectonics plays an important role in the evolution of global planetary climate and life. Yet, there is very little consensus on when and how plate tectonics began on Earth. Various scenarios have been proposed ranging from initiation of plate tectonics as early as after crystallization of magma ocean, to a relatively late start of plate tectonics, in the Late Archean. The most difficult aspect of plate tectonics is initiation of subduction. Although initiation of subduction has been extensively studied, the focus has been on the present–day Earth where plate tectonics is already occurring. The major difference between initiation of subduction on the present–day Earth and the early Earth is that in the absence of plate tectonic forces associated with plate tectonics are absent, and cannot participate in subduction initiation. Solomatov has developed constraints for this mechanism with the help of systematic finite element simulations in two dimensions (paper published) and began a systematic study in three dimensions (paper submitted). Two–dimensional studies showed that small–scale convection generates stresses comparable with the stresses required for initiation of subduction on the present–day Earth and can indeed be a trigger mechanism for plate tectonics. This conclusion seems to be even stronger in spherical geometry. The derived scaling relationships provide a theoretical basis for predicting plate tectonics on a silicate planet with arbitrary parameters.